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ARMORED MUD BALLS[1]
THEIR ORIGIN, PROPERTIES, AND ROLE IN SEDIMENTATION[2]

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ABSTRACT

A brief summary of the limited literature devoted to mud balls centers around nomenclature, the ideas regarding the origin of mud balls, and the factors limiting their size.

A report is made of a combined field and laboratory study in which an investigation of the size which mud balls may attain leads to conclusions that differ from those in the literature; findings are presented which deal with the relationship between sphericity and the distance mud balls travel, the influence of weight, sphericity, and specific surface upon armor quantity, and the importance of mud balls as a factor in the transportation of debris produced by erosion.

INTRODUCTION

Mud balls, both ancient and modern, are distributed widely throughout the world. For instance, in the United States they are present in the Patuxent formation on the Atlantic seaboard, the Pico formation in California, the glacial drift of the Great Lakes area, and the valley fills of New Mexico, Arizona, and Oklahoma, on

[1] Highly spherical masses of clay studded with pebbles remained unnamed until they were designated "pudding balls" by Cartwright in 1928, apparently because of their superficial resemblance to "pudding stone." Since the pebbles are not commonly distributed throughout the ball, as are plums in a pudding, but are usually restricted to the area at or near the surface where they form a protective coat, the author suggests the term "armored mud balls" as one which is more truly descriptive.

[2] Published with permission of the Soil Conservation Service, U.S. Department of Agriculture.

the shores of lakes with beach cliffs of clay wherever they may be located, and in hundreds of streamways in the southwestern quarter of the nation where the ephemeral nature of the streams makes it particularly easy to find them in large numbers.

Despite their ancient lineage and wide distribution they belong in a geological "no man's land," the category Kindle[3] has suggested for concretions, which they often closely resemble. It is surprising that a search of publications in English discloses only three short papers, all closely related, devoted exclusively to mud balls.[4] Two of these actually are more concerned in showing that some concretions may have originated as mud balls than in imparting information about mud balls as such.

Under various names[5] mud balls have received brief and infrequent mention in the geological literature of the past sixty or seventy years. In 1875 Jones and King[6] wrote of "clay galls" as much as 20 inches in diameter, upon the surfaces of which flint pebbles had become imbedded. During the present century Gardner, Haas, Ellis, Twenhofel, Wentworth, Cartwright, and others have written briefly of similar, though smaller, armored balls.[7] Ellis alone seems to have

[3] E. M. Kindle, "Range and Distribution of Certain Types of Canadian Pleistocene Concretions," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 609.

[4] James H. Gardner, "The Physical Origin of Certain Concretions," *Jour. Geol.*, Vol. XVI (1908), pp. 452–58; Leroy Patton, "In Support of Gardner's Theory of the Origin of Certain Concretions," *Jour. Geol.*, Vol. XXX (1922), pp. 700–701; William H. Haas, "Formation of Clay Balls," *Jour. Geol.*, Vol. XXXV (1927), pp. 150–57.

[5] Balls, galls, pebbles, cobbles, and boulders of clay and mud are commonly mentioned. Balls are highly spherical masses of clay produced in streams or other bodies of water. Galls are clay flakes, such as are commonly seen curling up on sunny floodplains, which have been incorporated in sand deposits, frequently after their shapes have been altered by breaking or rolling. In the nineteenth century even large clay balls were referred to as galls. Pebbles, cobbles, and boulders differ from one another only in size, the limitations being the same as for stones. Frequently they appear to have been shaped by flowing water rather than by being rolled along a smooth bottom, as in the case of balls.

[6] Rupert T. Jones and C. Cooper King, "On Some Newly Discovered Sections of the Woolwich and Reading Beds," *Quart. Jour. Geol. Soc. London*, Vol. XXXI (1875), pp. 451–57.

[7] Gardner, *op. cit.;* Haas, *op. cit.;* A. J. Ellis, a portion of a paper on clay balls recovered from glacial outwash published by Haas (*op. cit.*, pp. 152–53) in 1927; William H. Twenhofel, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins, 1932), p. 694; Chester K. Wentworth, "The Terminology of Coarse Sediments," *Nat. Res.*

made laboratory studies, the results of which were published in part after his death by Haas. The bulk of his work apparently has never been made available.

THE ORIGIN OF MUD BALLS

As to the origin of mud balls Gardner[8] suggested in 1908 that in the "super-saturated" streams of the Southwest a soft nucleus is formed by the cohesion of fine clay particles as they flow along a smooth bottom, in much the same way that butter is formed in a churn. These, he said, grow by the adhesion in concentric layers of clay, sand, pebbles, and other materials until the stream is no longer able to turn over the mass.

Gardner's view of the origin of mud balls differed radically from the one set forth by Jones and King[9] in 1875. The armored balls found upon beaches, they suggested, were formed by waves rolling chunks of clay that had fallen from neighboring cliffs. It is obvious from the text that these gentlemen were expressing an idea already generally accepted.

For nearly twenty years Gardner's hypothesis went unchallenged. Then, in 1927, after field investigations in the Southwest, Haas expressed doubt that large balls could be formed as Gardner suggested and added: "Of the scores which the author has broken apart not a single one showed a concretionary structure."[10] Haas agreed, however, that the size which balls may attain is determined by the ability of the stream to turn over the mass, and added "or by the narrowest part of the channel through which they have come."[11]

Coun. Bull. 98 (1935), p. 241; Lon D. Cartwright, Jr., "Sedimentation of the Pico Formation in the Ventura Quadrangle, California," *Bull. Amer. Assoc. Petr. Geol.*, Vol. XII (1928), p. 254.

[8] *Op. cit.*, pp. 454–55. Charles Terzaghi's studies on clay, first published in English seventeen years after Gardner suggested this hypothesis, show definitely that such a mass could not possibly be formed in the manner suggested. Gardner would have made no such error had Terzaghi's works been available to help him differentiate between the minute electrophysical forces of flocculation and those enormous surface-tension forces which are present when clay is in a plastic, semisolid, or solid state. Terzaghi found pressure intensities approaching 5,000 pounds per square inch in a blue marine clay as it reached its shrinkage limit (*Principles of Soil Mechanics* [McGraw-Hill Publishing Co., 1926], pp. 13 and 27).

[9] *Op. cit.* [10] *Op. cit.*, p. 157. [11] *Ibid.*

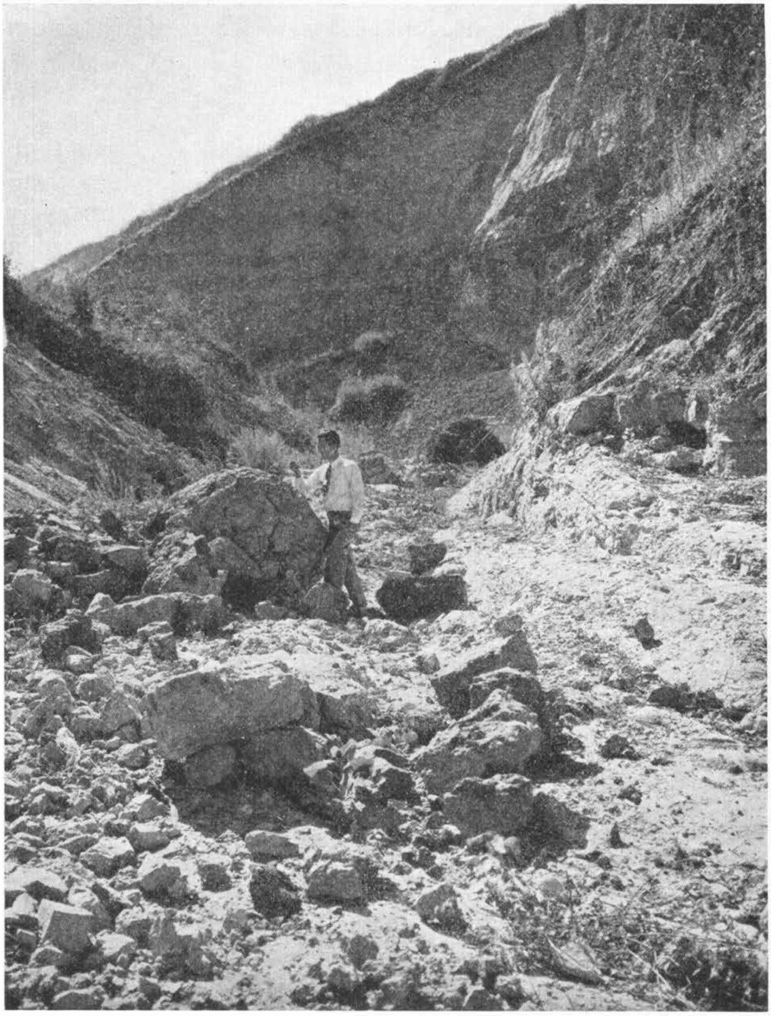


FIG. 1.—In Las Posas barranca. The beginning of the "assembly line" in a very productive armored mud ball factory in Ventura County, California.

The "pudding balls" found in the Pico beds of Ventura County, California, by Cartwright were occasionally of a concentric, banded structure as well as studded with pebbles. He suggests that they may have been "formed by accretion around a clay nucleus, such as a flake curling up between dessication [*sic*] cracks, which was caught by the renewed flow of a stream over its muddy bed, or the wash of sea water over a mud flat."[12]

FIG. 2.—Stranded mud balls. In times of flood a stream may produce mud balls in large quantities. The balls above were left stranded ten days before this picture was taken by Dr. N. A. Christensen. Many of the balls studied by the author were recovered from a small area adjoining this at the lower left.

Following the hurricane of mid-September, 1936, Kindle[13] observed clay balls as much as 10 inches in diameter on the beach at Cape May, New Jersey. Apparently these had been eroded recently

[12] *Op. cit.*, p. 254.

[13] "Post Hurricane Sea Shore Observations," *Amer. Midland Naturalist*, Vol. XVIII (1937), pp. 426–34; also Carey Croneis and David M. Grubbs, "Silurian Sea Balls," *Jour. Geol.*, Vol. XLVII (1939), pp. 598–612.

from beneath silty beds near the beach. Richter[14] states that clay balls may be formed beneath the surface of shallow seas by the erosion of older tidal deposits.

Twenhofel[15] also records the existence of concentrically banded balls and concurs with Wentworth[16] in the now generally accepted explanation that most mud balls are molded and abraded from chunks of clay which fall from the banks or are torn from the bottom of a stream or other body of water (Figs. 1 and 2). Both Twenhofel and Wentworth noted armoring and explained this as the accretion of pebbles and other substances to the mud balls through pressure. It thus becomes evident that concentric banding results when circumstances permit the accretion of clay fragments and other materials in alternate layers.

Ellis[17] noted that the pebble-filled exterior of balls could be peeled readily from the clay core and shared with Jones and King the distinction of reporting balls having diameters as great as 20 inches. Those mentioned by the other writers were, almost without exception, not over a foot in diameter and usually much smaller.

OPPORTUNITY FOR STUDY

Thus, briefly, may the literature of mud balls be reviewed. Recognizing the paucity of information available upon this interesting subject, we undertook field and laboratory studies under the most fortunate circumstances during the second half of 1938.

The mud balls themselves were supplied in superabundance by Las Posas barranca between El Rio and Camarillo, California. Literally tens of thousands of excellent specimens had been formed by this stream during a major flood, which inflicted severe damage upon Southern California during the first week of March, 1938.

Fortunately for the investigators, specimens were deposited in large numbers within a few feet of U.S. Highway 101 where, many months after the flood, they could readily be collected (Fig. 2). Those which had been exposed to the air were badly disintegrated

[14] Rudolph Richter, "Die Entstehung von Tongeröllen und Tongallen unter Wasser," *Flachseebeobachtungen zur Pal. u. Geol.*, XVI, *Senckenbergiana*, Band VIII, Heft 5/6 (1926), pp. 305–15.

[15] *Op. cit.*, pp. 693–94. [16] *Op. cit.*, p. 241. [17] *Op. cit.*, pp. 152–53.

and apparently confirmed a statement by Haas that they are never preserved unless completely covered at the time of the wash (flood). More than 200 balls, all freshly excavated, were selected for laboratory analysis, and additional hundreds were examined in the field.

So numerous were the balls that they formed an important part of a fill (Fig. 3) which had virtually obliterated a channel approximately 4 feet deep and 20 feet wide, made useless a triple culvert of con-

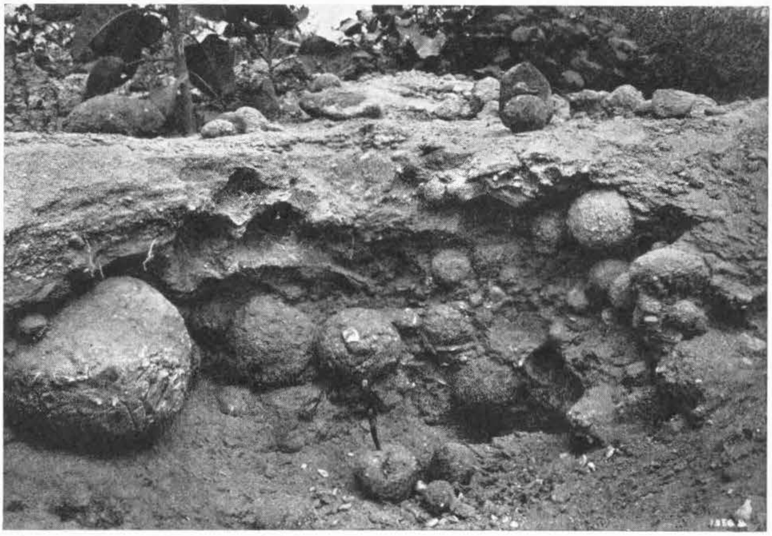


FIG. 3.—Cross section of a deposit of armored mud balls, Las Posas barranca, Ventura County, California. Large ball at left is approximately 12 inches in diameter. Knife at center gives scale.

crete, each rectangular section of which was 6 feet square, and had rolled by the thousand onto adjacent acres of farmland.

An investigation of the upstream conditions showed that Las Posas offered unusually favorable opportunities for studying the formation of mud balls. About $3\frac{1}{4}$ miles from Highway 101 the stream drops more than 50 feet through a concrete structure composed of a series of 5 deep, cylindrical, cushion pools.

Mud balls which formed above this structure—and they were plentiful—apparently were annihilated in passing through, since none was found for about 1,000 feet below it, and in the next 1,500 feet only very irregular clay cobbles and boulders were present. These contrasted strikingly with the highly spherical, heavily armored balls which were present in considerable numbers above the structure.

Half a mile downstream from the cushion pools a landslide involving several acres has been slipping into the barranca for half a century or more, forcing the water against the opposite bank, which is now vertical and fully 50 feet high. Of the 6 clays found in the balls of the deposit at Highway 101 (3 miles farther downstream) the 3 most commonly encountered were available here in enormous quantities (Fig. 4*a* and *b*). Evidently clay blocks which reached the stream, even though they could not be transported, were rounded rapidly by the water which flowed around them (Fig. 4*c*). About 1,000 feet farther downstream irregular clay cobbles and boulders were commonplace, but armored balls were not to be found (Fig. 4*d*).

Half a mile from the landslide nicely rounded clay boulders were abundant both on the surface and as exposed in gravel banks (Fig. 4*e*). Fairly good balls studded lightly with pebbles could be found with little difficulty. After another half-mile the lightly armored balls greatly outnumbered the clay cobbles and boulders. One unusually large specimen with a mean diameter of about 20 inches was found (Fig. 4*f*).

For another mile the streamway continued as a deep barranca, and increasingly spherical balls, into which pebbles were more and more deeply pressed, were to be seen stranded in many places or buried in bars laid down by previous floods. Evidence was everywhere to be had that this stream habitually produces excellent armored balls in time of flood.

A little less than 2 miles from the landslide the stream debouches upon the Plains of Oxnard and $1\frac{1}{4}$ miles farther on reaches Highway 101. The entire lower reach had been aggraded extensively during the March flood and subsequently had been excavated by a power shovel for a distance of nearly a mile. In the sides of this restored channel good specimens of armored balls were seen frequently. The increase in both armor and sphericity was observed readily as one journeyed the $2\frac{3}{4}$ miles from the slide to Highway 101.

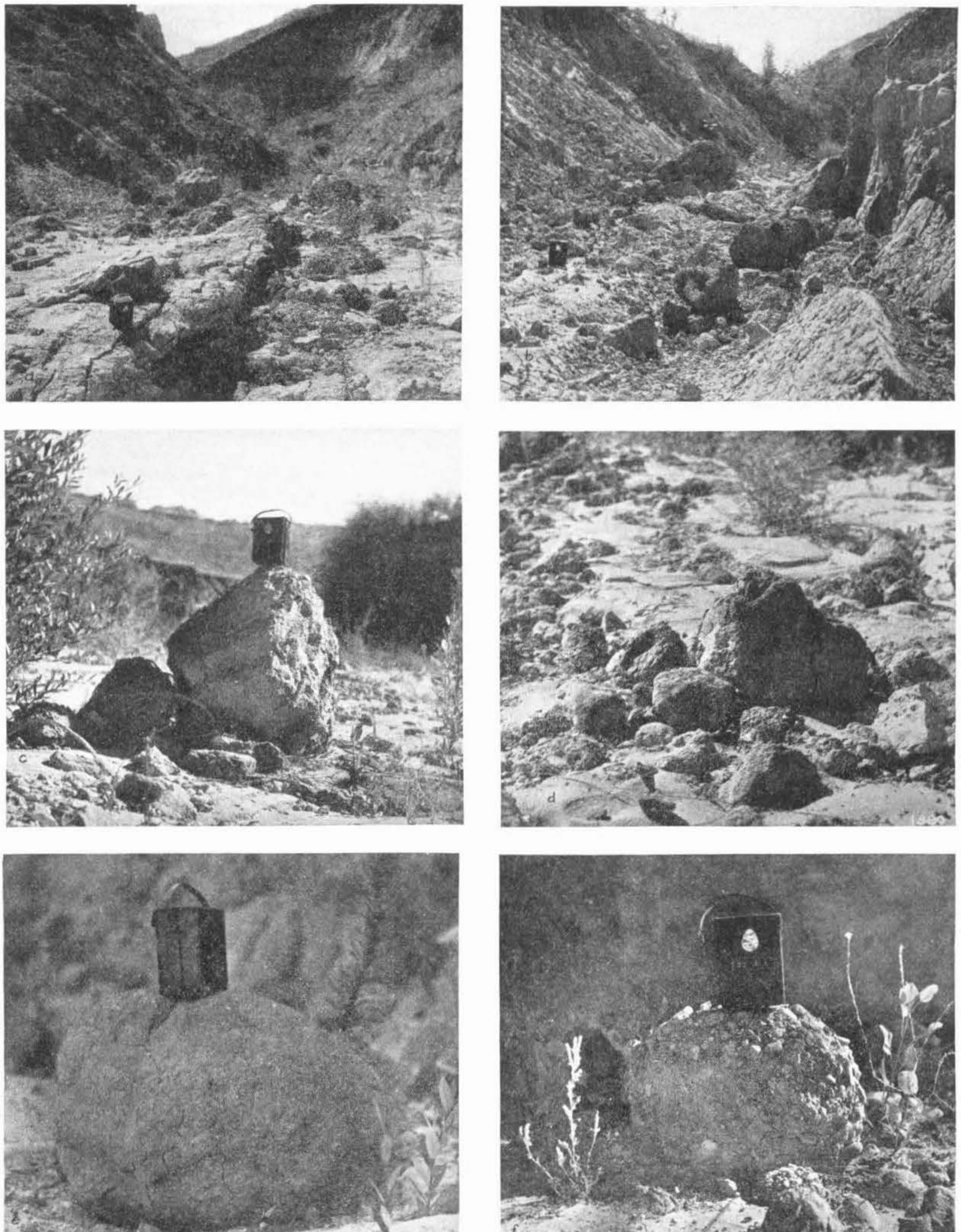


FIG. 4.—The development of armored mud balls. *a*, clayey material available from stream bed; *b*, material available from caving banks; *c*, clayey block rounded by flow of stream; *d*, clay boulder and cobbles after rolling approximately 1,000 feet; *e*, large clay boulder formed by rolling about 2,500 feet; *f*, ball armored after rolling about 1 mile.

Figure 3 shows a vertical section of a portion of the deposit from which the balls for laboratory study were recovered. The 2 balls at the extreme left, being respectively 2 and 12 inches in diameter, show the size range to be quite as great as might be expected in a bed of ordinary pebbles, cobbles, and boulders. A sample of 161 specimens, including those illustrated and others immediately adjacent, had a mean diameter of 2.9 inches and a frequency of occurrence greater than 1,000 per cubic yard. Since the yardage of the new deposits certainly ran into the hundreds and probably into the thousands, it is apparent that the number of balls produced by this stream during the March flood was enormous.

SIZE

Returning to the question of size, it may be well to recall that Gardner and Haas agreed that the size attained depended upon the power of the stream to turn over the mass. If this assumption is valid, is it not strange that, although there was abundant evidence that clay chunks over 30 inches in diameter were moved during the March flood, the largest mud balls commonly found were about 1 foot in diameter, and of the thousands seen not a dozen exceeded 14 inches? Two that had not been transported more than a mile had average diameters of approximately 20 inches.

Field observations indicate that only a fraction of 1 per cent of stream-made mud balls have diameters as great as 1 foot, although much larger masses could be transported easily by many streams in which small balls abound. When one recognizes that some balls grow by accretion while others are reduced in size by corrasion,[18] it becomes evident that the problem is a double one which involves not only the size to which a ball may attain but also the size it may maintain.

An analysis of the problem indicates that it is not one of transportation, as has been assumed, but rather one of structural strength wherein the forces tending to hold a ball together are opposed by those tending to destroy it. Cohesion is called upon to resist the destructive forces of impact, and the power to resist is quite obviously

[18] See Haas, *op. cit.*, p. 153.

proportional to the area under stress. In spheres the cross-sectional area varies directly as the square of the diameter, and it follows that, other factors being constant, a ball having twice the diameter of another offers four times as much resistance to any force which tends to break it in half.

But what of the impact forces to which a ball moving with a given velocity will be subjected upon striking a fixed object? These are obviously just as directly related to the mass of the ball as are the cohesive forces to its cross section. The mass of a ball increases as the cube of its diameter, and therefore the ball with a doubled diameter will be subjected to impact forces not four but eight times their former value. Therefore, it seems reasonable to believe that the size a ball may attain or maintain is determined by the point at which these factors reach a balance. For a ball of a given diameter, moving at a given velocity, the exact location of this point is determined largely by the cohesive strength of the particular clay involved, and with any clay this decreases with increasing wetness.

In an effort to establish the relationship between the forces of cohesion and impact, 40 freshly excavated balls of random sizes were dropped upon a concrete base from certain calculated heights. It was first thus determined that balls approximately 4 inches in diameter would just break when dropped 4 feet. Then it was assumed that a constant might be obtained by multiplying the square of the diameter D^2 of any ball by the height h it must be dropped to break it. When both lengths are measured in inches this constant, as indicated by the 4-inch ball, is $16 \times 48 = 768$.

A 2-inch ball tossed 15 feet into the air cracked so deeply when it struck that it was broken nearly in two ($D^2h = 720$); another, 8.6 inches in diameter, broke cleanly when dropped 10 inches ($D^2h = 740$). A 9.7-inch ball was dropped from a height of 8 inches (753) and broke; and, finally, a 9-inch ball, dropped 8 inches (648), was so deeply cracked that it fell apart when an attempt was made to lift it.

These tests indicated that the assumption was reasonable. Some 35 balls dropped from various heights during further investigations gave rather conclusive proof that if D^2h had a value of 740 or more, a clean break could be expected. With rare exceptions, if this value was less than 650, the ball was not broken, and in only one case did a ball hold together when this value exceeded 740.

The assumption that D^2h is a constant is apparently justified by these tests, but it should be kept in mind that the suggested numerical value (740) is not universally applicable. Had the balls tested been either wetter or dryer, for instance, a different value would have been obtained.

The determination of an approximate value for this constant makes it possible to calculate that a ball, similar to those used in the experiment, having a diameter of 7.9 inches would break if dropped 1 foot, while a drop of 1 inch would insure the destruction of a ball 27.2 inches through. A determination of the attained velocity shows that the small ball would be traveling 8 feet and the large one only 2.25 feet per second at the instant of impact. This throws much light upon the question of the maximum size a ball may attain or maintain.

Gilbert[19] has made measurements which indicate that the velocity of a bed-load particle once set in motion amounts to about 0.5–0.8 of the mean velocity of the stream, the higher values being valid for larger particles in shallow water—pertinent ones in the case of mud balls.

A ball 27.2 inches in diameter having a density of 1.7 will weigh about 650 pounds. Since ordinarily it must be abraded and molded from an even heavier chunk, let it be supposed that a clay cube of the specified density and with sides equal to the diameter of the ball, fell into a silty stream which had a specific gravity of 1.2. In air the cube would weigh approximately 1,235 pounds, but since it would displace 872 pounds of silty water, its effective weight in the stream would be only 363 pounds. If the stream had a mean velocity of 5 feet per second, the force it could exert upon the mass would be approximately 165 pounds[20]—less than one-half the effective weight of the cube.

[19] G. K. Gilbert, "The Transportation of Debris by Running Water," *U.S. Geol. Surv. Prof. Paper 86* (1914), p. 200.

[20] According to R. R. Daugherty (*Hydraulics* [New York: McGraw-Hill Book Co., 1937], p. 332) this force $= C_f wAv^2/2g$ when C_f = friction drag coefficient; w = specific weight of the fluid in pounds per cubic foot, A = cross-sectional area in square feet, v = velocity of the stream in feet per second, g = acceleration of gravity in feet per second.

Chang[21] states that theoretically a particle's effective weight in water is 40 per cent greater than the force required to move it along the bed. If this relationship holds for particles the size of our hypothetical cube, a velocity of 6.4 feet per second would be required to move it.

Once set in motion a bed-load particle rapidly attains its ultimate velocity, as many bed-load students agree, and our huge clay block would soon be moving at a speed of more than 5 feet per second—over twice the velocity needed to destroy it if it should strike any fixed object squarely. In such a stream, balls with diameters of 8 inches might survive nicely, but all larger ones would be in grave danger of destruction.[22]

Although the variables which affect the formation of clay balls are numerous, the students of sedimentation should be able to gain much qualitative information regarding upstream conditions which existed at the time any group of mud balls was being formed by carefully studying the balls themselves.

Assuming that the balls studied are typical—and there are admittedly insufficient data available to justify such an assumption—if the diameter of the largest ones commonly found in a deposit is approximately 8 inches, the maximum velocity of the stream in which they were formed was probably in the neighborhood of 8 feet per second, since balls of this size may be expected to break up at that speed if they strike any obstruction squarely. In such a stream, according to Gilbert, the maximum speed the bed load could attain would be 6.4 feet, certainly perilously close to the limit an 8-inch ball could endure. Balls a foot in diameter would indicate velocities of not over 5 feet per second, a velocity only slightly greater than is required to move them. Four-inch balls would indicate a stream velocity of 16 feet per second; 2-inch balls a velocity twice as great. One should not lose sight of the fact that small balls might result in streams of low velocity when only small chunks are initially available, as might be true when varved clays are involved.

[21] Y. L. Chang, "Laboratory Investigation of Flume Traction and Transportation," *Proc. Amer. Soc. Mech. Eng.*, Vol. LXIII (1937), pp. 1729 and 1737.

[22] In making these calculations many assumptions have been made, perforce, and values given are to be taken only as rough indications of the order of magnitude of forces and sizes.

The rolling process is essential to the formation of clay balls with high sphericity, and, therefore, unless clay chunks can roll freely, such balls cannot be expected to develop. It is of interest, in this connection, that the mud balls observed in this investigation and during the previous 10 years invariably have been large in comparison with the average size of the particles which formed the bed of the stream that produced them (Fig. 3). It follows that clay "golf balls" will not be produced in a stream the stable bed of which is composed largely of stones the size of grapefruit, oranges, or even golf balls. During periods of low water and moderate velocities the clay fragment would find itself in some snug cranny, and when floods came it would be crushed or smashed to bits by the heavier elements of the bed load. Clearly the size of the particles which form the stream bed tends to limit the minimum size of the balls which may be produced. Like balls of maximum size, then, the smallest balls may record facts about the stream which made them.

Too, the mere presence of clay balls in considerable numbers indicates that the parent stream was cutting laterally and possibly downward at a rapid rate at the time of their formation and that its banks or bed contained large quantities of clay. Conditions that lead to extensive undercutting of banks or to rapid headward erosion are ideal for the production of clay balls.

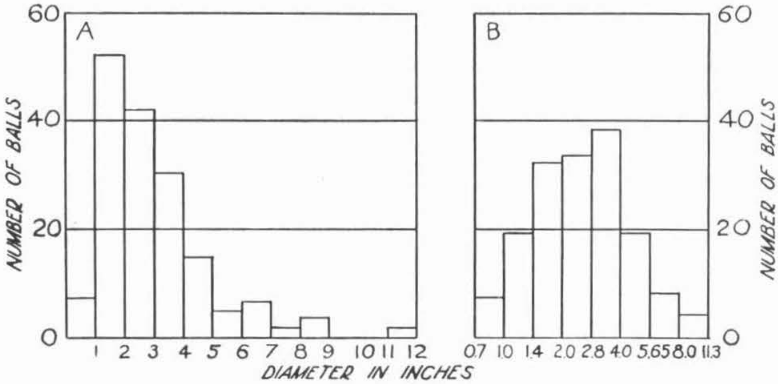
SPHERICITY

The most striking characteristics of the Las Posas balls recovered at the roadside deposit are their high degree of sphericity[23] and uniformly heavy armor of pebbles. In computing the sphericity values, Wadell's[24] method was used. The ratio between the diameter of a sphere having the same volume as the ball and the longest diameter

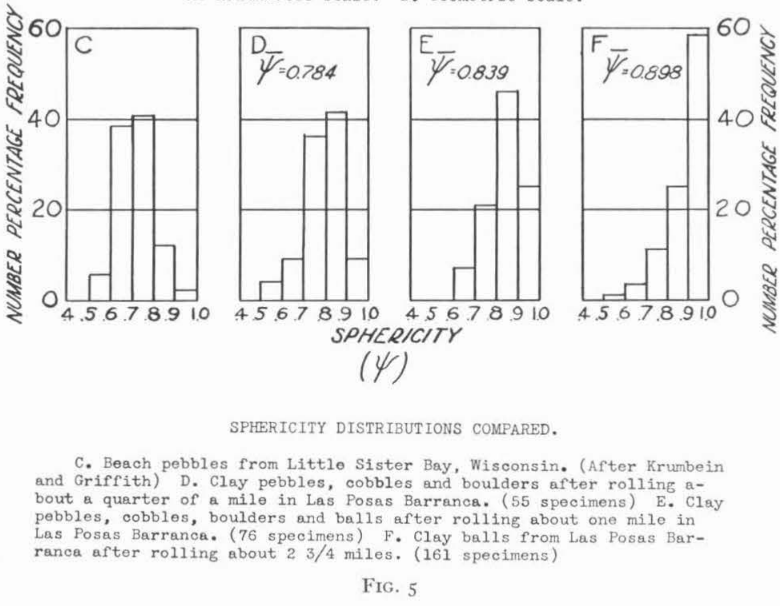
[23] "Wadell appears to be the first to differentiate between *shape* (sphericity) and *roundness* and to show that these are two independent variables. Wadell pointed out that roundness was a matter of the sharpness of the corners and edges of a grain, whereas shape has to do with the form of the grain independently of the sharpness of its edges. . . . . Wadell, therefore, used the sphere as a standard of reference and spoke of the 'degree of sphericity' as the measure of the approach of other solids to the sphere in form" (W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography* [New York: D. Appleton-Century Co., 1938], p. 283).

[24] Hakon Wadell, "Shape Determination of Large Sedimental Rock Fragments," *Pan. Amer. Geol.*, Vol. LXI (1935), pp. 187–220.

of the ball was obtained. The volume was computed using the three diameters and the equation for the volume of a triaxial ellipsoid.



SIZE-FREQUENCY DISTRIBUTION OF 161 MUD BALLS FROM LAS POSAS BARRANCA, VENTURA COUNTY, CALIFORNIA.
A. Arithmetic scale. B. Geometric scale.



SPHERICITY DISTRIBUTIONS COMPARED.

C. Beach pebbles from Little Sister Bay, Wisconsin. (After Krumbein and Griffith) D. Clay pebbles, cobbles and boulders after rolling about a quarter of a mile in Las Posas Barranca. (55 specimens) E. Clay pebbles, cobbles, boulders and balls after rolling about one mile in Las Posas Barranca. (76 specimens) F. Clay balls from Las Posas Barranca after rolling about 2 3/4 miles. (161 specimens)

FIG. 5

The results of these calculations are shown graphically and compared with a sample of beach pebbles as presented by Krumbein and

Griffith[25] (Fig. 5, *C* and *F*). Notice that nearly 60 per cent of the balls have sphericities which exceed 0.9. What cannot be learned from the histogram is that 32 per cent had sphericities above 0.95, 12 per cent above 0.99, and nearly 7 per cent had a sphericity of 1.00. Measurements were made only to the nearest tenth of an inch; even so, it is noteworthy that one ball in each 14.6 qualified as a sphere.

The high average sphericity of mud balls is not without importance. Gilbert[26] has pointed out that a particle may be transported in four ways, depending upon its shape, size, and density. It may slide along the bottom, it may leap, it may roll, or it may be carried in complete suspension. Suspended particles move most swiftly, but the rolling ones outstrip those which leap or slide. Clay chunks, by becoming round enough to roll, actually speed up their transportation. Not infrequently such balls have dry interiors while they are in transit, which indicates that much of their initial buoyancy is retained. Both their attained sphericity and their conserved buoyancy tend to increase the efficiency of the destructive forces of erosion by easing the stream's transportation burden.

So rapid is the development of clay balls (Fig. 4) that it seems entirely within the realm of possibility that their attained sphericity might be used with a fair degree of accuracy for estimating the distance to source material. A determination of percentage by weight of armor should increase the dependability of such estimates. Although reasonable accuracy might demand such an elaborate study of the character of the clay involved that it would make the method entirely impractical, data are insufficient at present for conclusions to be drawn.

The idea of using roundness measurements for this purpose has been suggested by Wentworth,[27] who measured river pebbles that had traveled known distances and then constructed a "roundness-distance curve." "One of the most valuable applications of the

[25] W. C. Krumbein and J. Scott Griffith, "Beach Environment in Little Sister Bay, Wisconsin," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 629–52.

[26] *Op. cit.*, p. 200.

[27] "A Field Study of the Shapes of River Pebbles," *U.S. Geol. Surv. Bull. 730 C* (1922), pp. 103–14.

roundness-distance curve," he wrote, "is in determining the distance certain pebbles have traveled by a measurement of their roundness." Not only is the sphericity of mud balls much more readily deter-

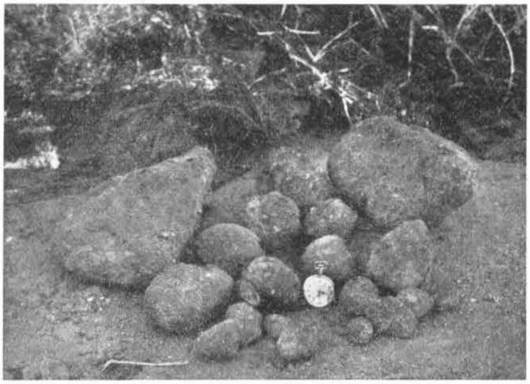


FIG. 6a.—Group of clay boulders, cobbles, pebbles and balls dug from a gravel bar about $\frac{1}{4}$ mile below their point of origin.

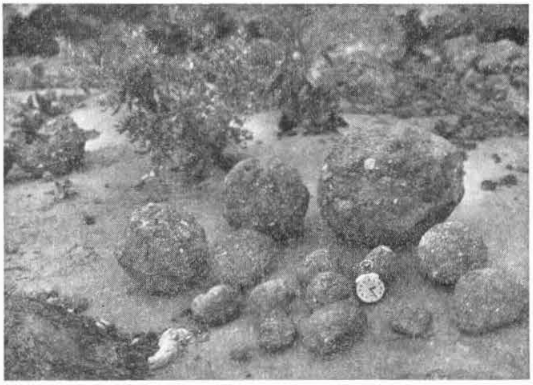


FIG. 6b.—Group of lightly armored clay pebbles, cobbles, and balls about 1 mile below their point of origin. Like those in Fig. 6a, these were found in a gravel bar. Notice the great increase in sphericity.

mined than is the roundness of pebbles, but also the range of physical conditions under which mud balls are formed is so greatly restricted that their use in estimating distances traveled should be comparatively simple.

With this in mind, three stations were selected at which the specimens measured were known to have traveled approximate distances of $\frac{1}{4}$ mile, 1 mile, and $2\frac{3}{4}$ miles, respectively (Fig. 6*a*, *b*, *c*). Mean sphericities were found to be 0.784, 0.839, and 0.898 at these points (Fig. 5, *D*, *E*, and *F*). These data indicate that in this particular instance the sphericity varies as the cube root of the distance traveled. It must not be forgotten that three points are insufficient to determine the type of a curve accurately and that at zero distance

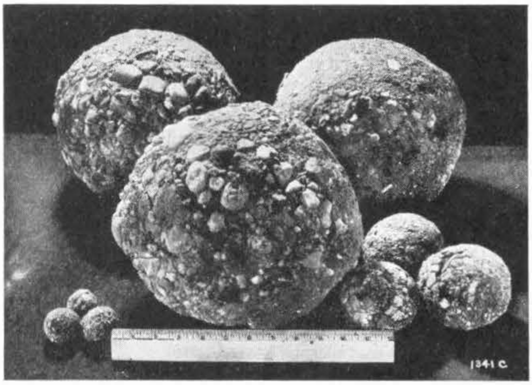


FIG. 6*c*.—Finished products such as these result when crude clay blocks have rolled approximately 3 miles in Las Posas barranca. Note the remarkably heavy pebble armor and the high degree of sphericity.

the sphericity is not zero but a finite value. For instance, a cube and a block $1 \times 1 \times 2$ have sphericities of 0.716 and 0.637, respectively.

ARMOR

Investigation of the armor held much of interest. Rather convincing proof of the geological period to which the balls belong was supplied by an armor pebble which proved to be a bottle cap. In another case a small finishing nail was incorporated in the armor. Frail gastropod shells were occasionally as perfectly preserved as if they had been packed in cotton. Selenite crystals were sometimes present and scarcely scratched.

Having observed that there was an apparent geometric similarity in the size distribution of the armor particles on balls of various

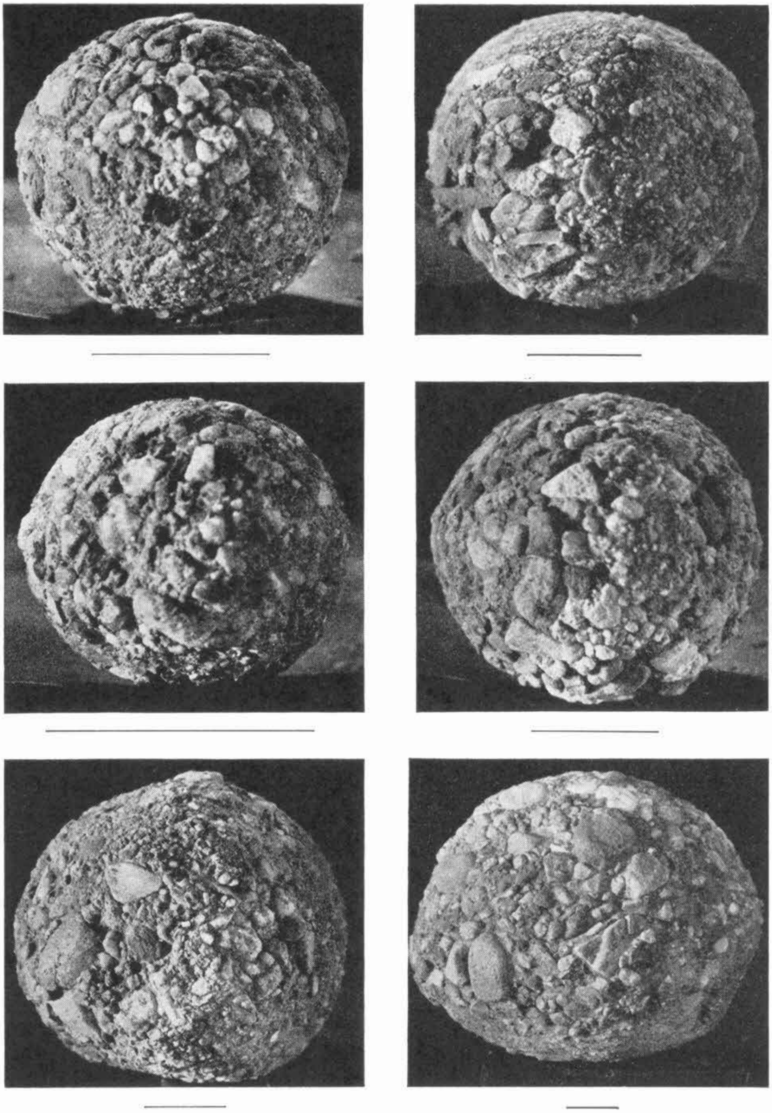


FIG. 7.—Las Posas mud balls. These six balls illustrate the geometric similarity in the size distribution of the armoring particles on balls of widely differing diameters. The line beneath each represents 1 inch.

diameters, we made a series of six photographs in such a way that the photographic image had approximately the same diameter in each case. The resulting pictures are shown in Figure 7 with a line drawn beneath each to represent 1 inch. So convincing was this approach that mechanical analyses were made of the armor of a series of balls. Computations made from these analyses confirmed the photographic evidence of armor similarity. Figure 8 shows the core of a

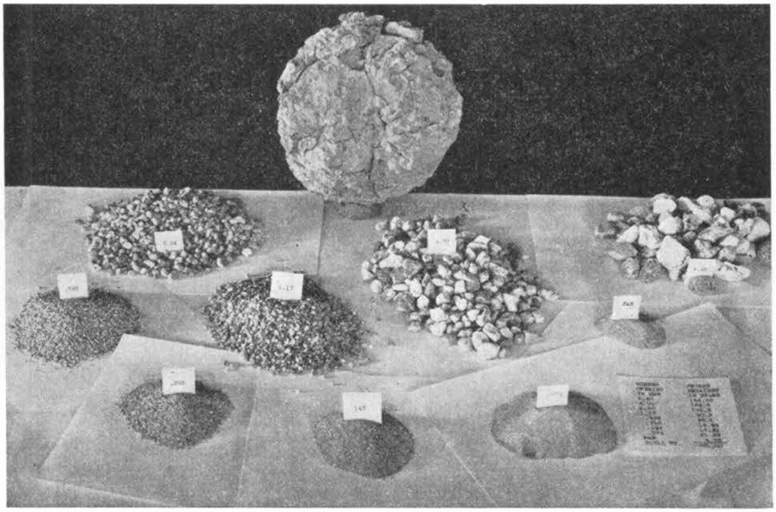


FIG. 8.—A mud ball and its armor. The quantity of armor a single ball may acquire is often astonishing. The armor shown above has been separated into nine grades by sieving. The original ball was just an average one from Las Posas barranca.

large ball surrounded by its armor which has been separated by sieving into nine grades.

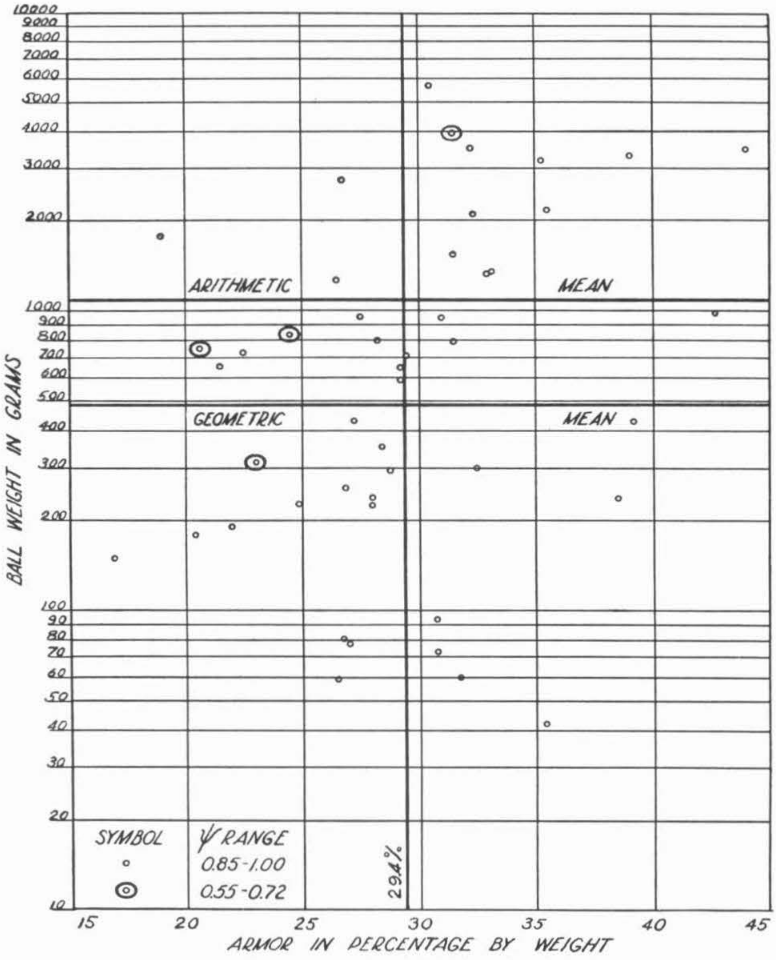
In another investigation 47 balls were picked at random, weighed, and stripped of their outer shells which consisted of sand and pebbles held together by a clayey matrix contributed almost entirely by the original core of the ball. All fines were removed by washing, and the remaining coarse material was oven dried and again weighed. This residue was considered to be the armor of the ball, although it was recognized that it contained sand and, in some instances, small concretions and shell fragments derived from the block from which the ball had developed. In extreme cases as much as 7 per cent of this so-called armor was supplied by the matrix, but the average probably was less than 3 per cent.

The portion of the total weight of a ball that could be attributed to armor varied from 17.1 per cent to 44.0 per cent, the mean value for the 47 balls being 29.4 per cent. The data obtained are shown in a scatter diagram (Fig. 9), which indicates that the general tendency is for the heavier balls to have a higher percentage of armor than the lighter ones.[28] Of the 14 balls with weights greater than the arithmetic mean (1,086 gm.) only 3 had less than average armor. The average for the group was 32.1 per cent. The 26 balls with greater than geometric mean weight (486 gm.) had a group average of 30.3 per cent, and 15 had heavier-than-average armor. There were 21 balls below the geometric mean weight having an average armor weight of 27.5 per cent.

Balls weighing less than 100 gm. appear to constitute a nonconformist group, but the specimens are too few to allow conclusions to be drawn safely. If, however, their remarkably heavy armor is not purely accidental, several reasonable explanations may be advanced: (1) that they are remolded fragments of larger armored balls, (2) that their total weight is so small that the percentage of armor would be influenced greatly by the adherence of a very few large pebbles, and (3) that, since armoring is a surface phenomenon, the influence of a very high surface area per unit of volume is coming into play. A sphere with a diameter equal to unity will have 6 units of surface for each unit of volume, but if the diameter is increased to 4, it will have only 1.5 surface units for each 1 of volume. The effect of this rapidly decreasing ratio apparently is more than offset in all but the smallest balls by the increasing weight which tends to imbed pebbles more deeply. Yet the depth to which a pebble may penetrate is limited also by the thickness of the plastic layer that surrounds a more or less

[28] If the percentage of armor by weight for this same group of balls is plotted against the mean ball diameter, the larger balls and the very smallest balls again show this tendency to armor more heavily than those of intermediate size.

dry center and, consequently, it would not be surprising to find that the armor ratio falls appreciably on balls larger than those already



PERCENTAGE OF ARMOR IN RELATION TO TOTAL WEIGHT
FOR 47 MUD BALLS FROM LAS POSAS BARRANCA,
VENTURA COUNTY, CALIFORNIA. 1938.

FIG. 9

investigated. The heaviest ball shown in Figure 9 may indicate such a trend. It seems entirely possible, too, that stickiness, rather than weight, plays the leading role in armoring balls such as the smallest represented in the diagram.

Three of the 10 balls having armor ratios below 25 per cent resembled footballs more closely than spheres (Fig. 10). The same shape characterized the ball with the lowest percentage of armor in the group of 5 weighing between 3,000 and 4,000 gm. (Fig. 9), but the analyses made were insufficient in number to justify the conclu-

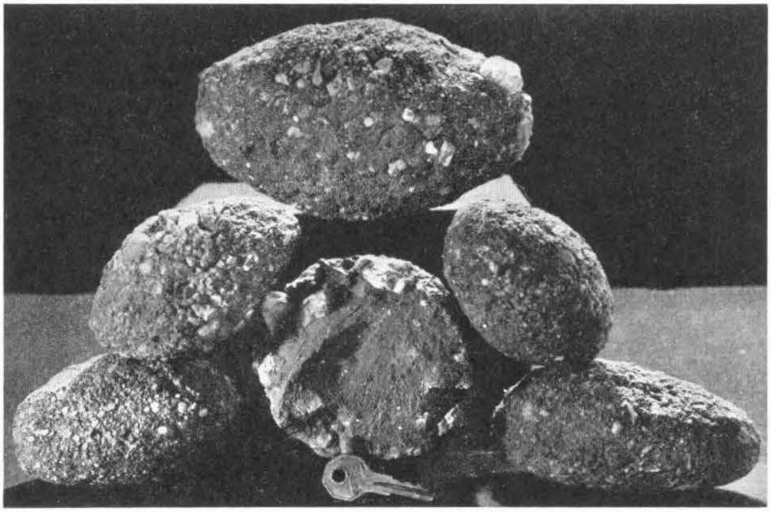


FIG. 10.—Mud "footballs" and "potatoes." Balls of this type were frequently found in the Las Posas deposit. That they tend to become most heavily armored in the region of their minor axis is shown conspicuously by the specimen in the center at the left. It seems probable that the cores originally were elongate blocks.

sion that low sphericity is regularly accompanied by lighter armor. Such a possibility is indicated, however, and examination in the field apparently confirms this view. Furthermore, a ball of the football type tends to revolve exclusively about its major axis and, as a consequence, can become armored heavily only upon its minor circumference.

The rolling process is obviously essential to high sphericity and therefore the farther a clay block rolls—assuming a favorable stream bed—the better are its chances of becoming a sphere (Fig. 5, *D*, *E*, and *F*), the softer its exterior becomes, and the greater is the number of pebbles with which it comes in contact. Since this increased softness makes it possible for the pebbles encountered to be pressed in more readily and more deeply and since high sphericity allows a ball to rotate on various axes, it is only reasonable to expect heavier armor.

In the balls examined pebbles frequently penetrated for a distance equal to one-fourth the radius of the ball, and sometimes even twice

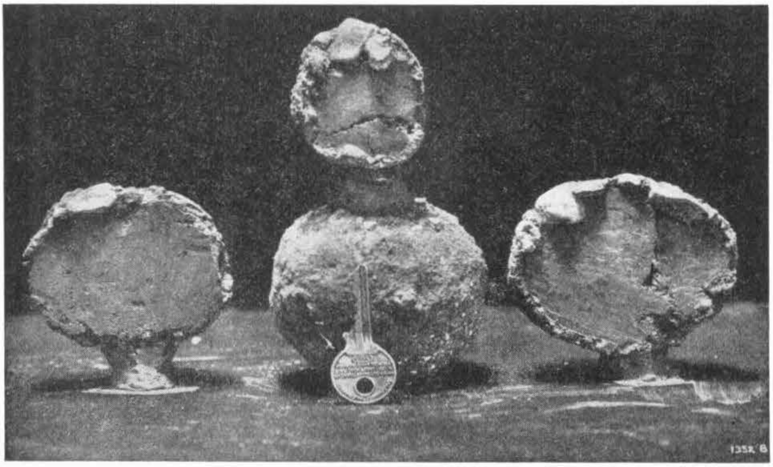
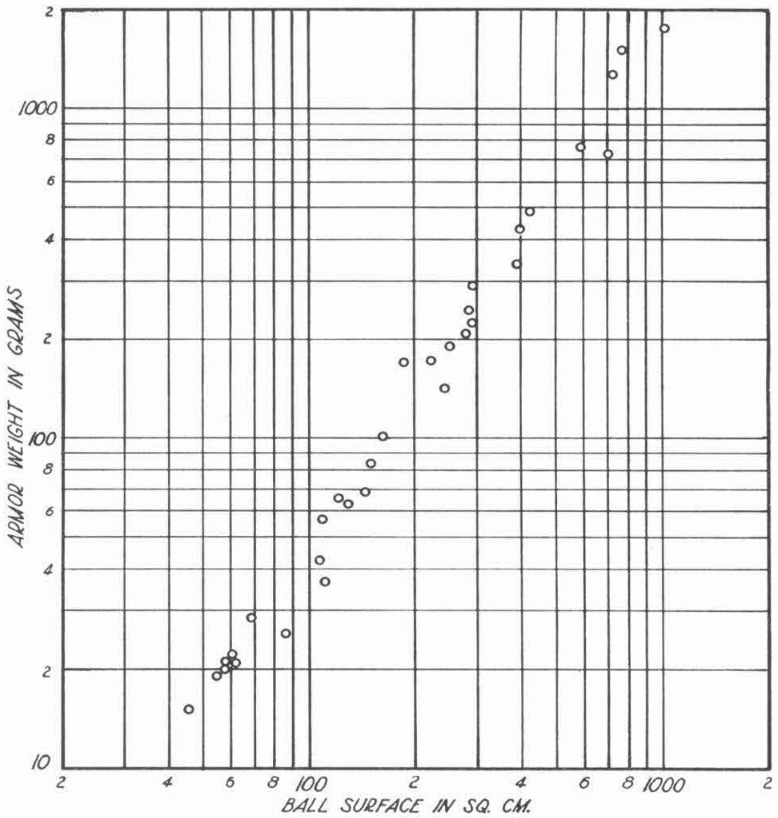


FIG. 11.—Lopsided armoring. Balls such as these may be re-rounded fragments of larger balls which had become armored before breaking to pieces. The small ball in the center is an extreme case.

as deeply, but as a general rule the armoring shell was not very thick. Usually when pebbles penetrated to great depths, they did so on one side only and were of sizes which appeared large for the specimen upon which they were found (Fig. 11). There is good reason for believing that such balls are fragments broken from larger ones which had become armored. It is also probable that the unusually high percentage of armor shown by certain small balls, such as the group of three shown in Figure 9 with weights between 200 and 500 gm., may be explained in the same way.

Obviously, then, the quantity of armor on any ball has been influenced by a host of variables, a list of which would almost certainly include the permeability, specific gravity, volume, and stickiness of the clay nucleus, the distance it has come and the rate of travel



THE RELATIONSHIP BETWEEN ARMOR WEIGHT AND SURFACE AREA

Thirty-two armored balls from Las Posas Barranca, all with sphericities greater than 0.9, are represented.

FIG. 12

(variables which may greatly influence both size and sphericity), the velocity and specific gravity of the stream, and the availability and density of suitable armoring material. In the wake of this incomplete though imposing list, it is clear that conclusions drawn from Figure 9 must be recognized as tentative ones.

Since armoring is essentially a surface phenomenon, it was thought that a method of plotting which emphasized area rather than weight would be more consistent. With this in view 32 balls, all with sphericities greater than 0.9, were selected and their armor weights plotted against their surface areas. Figure 12 resulted and presents a much more convincing picture than Figure 9, even permitting the conclusion that the total quantity of armor is a power function of the surface area and can be expressed, in this case at least, with reasonable accuracy as $W \propto A^{1.54}$.

Thus it becomes evident that the larger balls may be expected to be more heavily armored than the smaller ones, a conclusion that confirms the one previously drawn from Figure 9, namely, that the heavier balls tend to have a higher percentage of armor than the lighter ones. Since the balls varied in specific weight from slightly less than 1.5 to slightly more than 2.0, it can readily be seen that balls of equal size might vary considerably in weight.[29]

The proportionality just expressed indicates that the weight of armor per unit area is approximately a linear function of the ball diameter. This relationship may be stated more generally by introducing the effective specific weight of the ball: thus $W / D^2 = C(\nu_b - \nu_w)D$, where W is the total armor weight, D the diameter of the ball, C the constant of proportionality, ν_b the specific weight of the ball, and ν_w the specific weight of the fluid in which the ball is produced.

SHELLS

In describing the armored balls he recovered from glacial tills, Ellis stated: "The shell was not so firmly fixed to the nucleus it could not be readily peeled off."[30] This characteristic of armored clay chunks probably is almost entirely responsible for the belief that both clay and pebbles commonly are added to the exterior of the

[29] Although all the balls represented in Fig. 12 were formed by one stream during a single flood, they contained clayey cores of at least 6 kinds and varied in weight from 42 to nearly 5,800 gm., and so covered the entire range upon which the laboratory investigations were made.

[30] Quoted by Haas, *op. cit.*, p. 153.

rolling masses and that there is practically no limit to the size which they may reach if only the stream can continue to roll them.

Although occasional balls do show clearly that both clay fragments and rock pebbles have been added to form the armoring coat, the percentage of such balls apparently is small. Ordinarily it is obvious that the pebbles have been forced into the soft outer layer of the clay chunk, and, since the matrix for the armor must be supplied from within, an average ball cannot be expected to increase its size greatly by accretion of pebbles. As soon as it becomes well covered, it has almost sealed itself against any further intrusions. Pebbles which penetrate beyond their own diameters must be driven in by impact against other external hard substances. Just how far they may intrude will depend largely on the depth to which the ball has become wet and to a lesser degree upon the weight of the ball and the velocity of the stream.

A large number, perhaps the majority, of clay balls, whether armored or not, have dry interiors at the time they are deposited. This statement may be questioned by many readers, but recent field studies have shown that the time required to convert an angular clay block into a highly spherical ball with a fair coat of pebbles is frequently less than 15 minutes, while a well-rounded pebble or boulder of clay may be produced in a very few minutes. When this speed of formation is coupled with the rapid decrease in the rate of absorption which accompanies the wetting of dried clay and with a further decrease caused by the acquisition of a coat of armor, it is easily seen that the interior of a ball is very effectively sealed against any rapid penetration of moisture. Such considerations justify Haas's statement that "if they are broken apart shortly after they come to rest, the major part of the interior of the larger ones may be perfectly dry with a moisture penetration of less than an inch."[31]

Because of the way in which balls become armored, it may seem strange that the outer shell peels so readily. If balls were so deposited that only their exteriors ever became wet, the shell probably would not peel. By the very nature of things this is rarely the case, for, although a ball may be quite dry inside when deposited, it is ordinarily gradually wet through after it comes to rest. Taken from

[31] *Op. cit.*, p. 157.

the earth in this condition, the shell clings tightly, but if the ball is exposed to the air for a few hours, or for a few days in the case of large ones, the shell often becomes loose, frequently so loose that it falls off.

The core of a ball usually is composed of relatively pure clay and silt with high shrinkage factors, while the shell contains only from 20 per cent to 50 per cent of such material, the remainder consisting

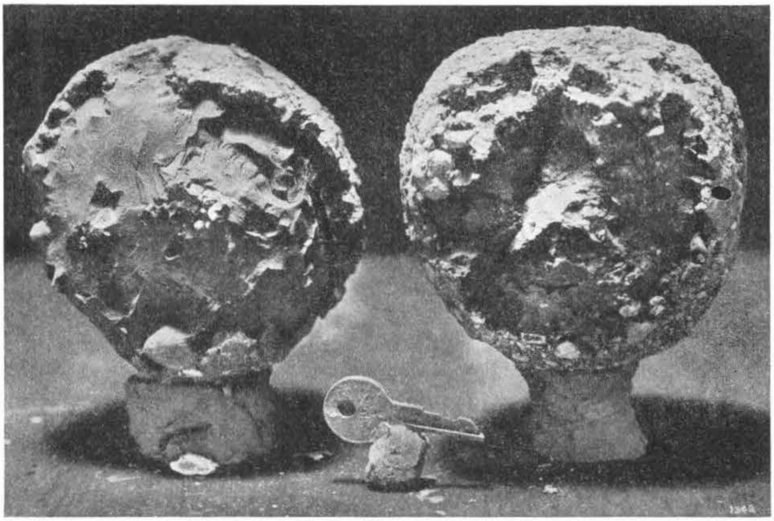


FIG. 13.—Mud balls after drying. Armor has spalled from the ball on the left, leaving the core of fine-grained blue clay intact. The one on the right, composed of coarse-grained, brown, gypsiferous clay, has been deeply penetrated by drying cracks.

of sand, pebbles, and similar substances, most of which have a shrinkage factor of zero.[32] Consequently, when drying takes place after deep wetting, the core actually shrinks away from the shell, which may then be readily removed (Fig. 13).

THE ROLE OF MUD BALLS IN EROSION AND SEDIMENTATION

It may be well at this point to review certain facts which have been previously set forth: (1) blocks of clay rapidly attain high

[32] Thirty-seven shells averaged 30.7 per cent fines and water-soluble material by weight, the extremes being 21.0 per cent and 44.6 per cent.

sphericity while being transported by a stream, (2) bed-load particles that roll travel more swiftly than those that leap or slide, (3) clay balls, by conserving their dry interiors during transportation, frequently retain a portion of their original buoyancy, and (4) approximately 30 per cent of the total weight of the balls examined was supplied by sand, gravel, and other substances picked up in transit by the rolling clay masses.

High sphericity, conserved buoyancy, and the ability to acquire armor combine to make mud balls powerful and efficient vehicles for the transportation of erosional debris as bed load. Therefore, by converting irregular clay chunks into self-armoring balls, a stream may so increase the efficiency of its transportation methods that it may readily roll away enormous quantities of material which it otherwise would be forced to abandon.

Certainly this method of moving debris speeds up appreciably the cutting of gullies in regions where clayey soils predominate. Rough estimates, which are thought to be conservative, indicate that nearly 500 tons of clay and 200 tons of gravel were removed as armored mud balls from $1\frac{1}{2}$ miles of Las Posas barranca during the single flood of March, 1938.

Mud balls make it possible not only to move larger loads but also to move them farther. Ordinarily in debouching upon a fan or into a flood plain, a stream soon abandons the larger units of its bed load and deposits much of its suspended load as well. Alluvial fans themselves are proof enough of this fact. If the stream bed be firm and smooth, mud balls may continue far out into the distributaries, even when the depth of the stream has become less than the diameter of the transported ball.

Since mud balls are large in comparison with the particles which form the stable bed of the streams in which they are produced, it is not strange that they are usually deposited in locations where ordinary cobbles are rare and boulders quite unknown. In such a place in their final role they play the part of the missing stones, and this they do remarkably well (Fig. 3).

CONCLUSIONS

In conclusion, it may be well to summarize and restate the facts which these studies of clay balls seem to show:

1. Almost all mud balls are formed from blocks of clayey material which have caved from the banks or have been torn from the bottom of a stream or other body of water and then have been abraded or molded into highly spherical forms. Terzaghi's studies on the properties of clay make it clear that such balls cannot be formed from soft nuclei in the manner Gardner suggested.

2. Contrary to the belief of Gardner and Haas, the maximum size of balls is not "limited only by the power of the stream to turn over the mass," but by a balance between forces of impact and forces of cohesion. Experiments indicate that the velocity with which a ball may move with safety in a stream is inversely proportional to its diameter. Although armored balls as large as 20 inches in diameter are usually found only in lakes and seas, they occasionally occur in streams at no great distance from the source of their core material.

3. The minimum size of balls appears to vary with the average size of the particles that compose the stable bed.

4. Armored clay balls studied (all from one locality) approach geometrical similarity both in the appearance and in the actual size distribution of their armor particles.

5. A ball armors itself by pressing pebbles into its softened exterior, and, although it may thereby increase in size, a heavy coat of gravel virtually eliminates further growth.

6. High sphericity and complete armoring are the results of rolling upon a relatively smooth stream bed. Other factors being constant, the quantity of armor attained is a power function of the surface area of the ball.

7. The armor coat peels or spalls from a ball because of the relatively high shrinkage of the clay core and the low shrinkage of its pebble-filled "shell."

8. The effectiveness of a stream in removing erosional debris from an area in which clayey materials predominate may be greatly increased by the tendency of clay blocks to attain spherical shape rapidly and to armor themselves readily with gravel.

9. Further careful study of balls formed from a considerable num-

ber of clays under various conditions may furnish geologists with a means of estimating maximum velocities of ancient streams, the nature of their bed material, approximate distances to source material, and the kind of water body which formed them.

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